ERDC MSRC PET Technical Report No. 01-16

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11 May 2001

Work funded by the Department of Defense
High Performance Computing Modernization Program
U.S. Army Engineer Research and Development Center
Major Shared Resource Center through

Programming Environment and Training

Supported by Contract Number: DAHC94-96-C0002
Computer Sciences Corporation

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Abstract

The COupled MArine Prediction System (COMAPS) is a parallel-processing, numerical modeling system that simulates the physical conditions of coastal waters. The system consists of the CH3D-SED circulation and sediment transport model, the WAM wind-wave model, and the WCBL bottom boundary layer model. COMAPS includes traditionally neglected, but potentially important, physics couplings between wave and current motions at the water surface and wave, current, and sediment motions at the marine bed. COMAPS has been developed by the Programming Environment and Training program at the U.S. Army Engineer Research and Development Center. In the past year, significant upgrades have been made to COMAPS. The initial fully functioning version, COMAPS 1.0, exhibited convergence problems in deep water and very shallow water regions. In addition, sediment transport predictions in shallow regions appeared to be excessive. These issues have been resolved in COMAPS 2.0 through the enhancement of numerical iteration schemes, the use of a pure current bottom boundary layer in deep water, and the improvement of sediment transport physics in terms of both accuracy and inter-model consistency. These improvements will result in more accurate wave, current, water elevation, and sediment transport predictions for the support of military activities.

1. Introduction

This report documents upgrades made to the COupled MArine Prediction System (COMAPS) during year 5 of the Programming Environment and Training (PET) program at the U.S. Army Engineer Research and Development Center (ERDC). COMAPS is a numerical modeling package consisting of coupled, parallel-processing versions of the CH3D-SED circulation and sediment transport model (Chapman et al., 1996; Spasojevic and Holly, 1994), the WAM wind-wave model (WAMDI, 1988; Gunther et al., 1992), and the WCBL marine bottom boundary layer sub-model (Welsh et al., 2000). COMAPS generates nonstationary, nonuniform predictions of three-dimensional currents, temperatures, salinities, and sediment concentrations, and two-dimensional water surface elevations and frequency-direction wave-spectra. The inclusion of traditionally neglected coupling mechanisms in the air-sea and bottom boundary layers means that COMAPS predictions will be more accurate than those made by the stand-alone, uncoupled component models. This improvement in accuracy and the allied superior performance of parallel-processing codes will result in enhanced support for military activities, which has been the motivation for the development of COMAPS. These activities include fleet navigation, harbor management and safety, amphibious landings, the detection of submarine craft, and the disposal of dredged material.

COMAPS has been developed through a series of year-long Focused Efforts sponsored by the ERDC PET program (Zhang et al., 1998; Welsh et al., 1999; Bangalore et al., 1999; Welsh et al., 2000). The first fully-functioning version, COMAPS 1.0, was documented in Welsh et al., 2000. As explained there, version 1.0 had convergence problems in both deep water (typically deeper than 100m) and very shallow water (typically less than 4m) because the WCBL model was unable to reach a solution. This resulted in standard, uncoupled model formulations being retained at numerous grid points. Furthermore, COMAPS 1.0 appeared to predict excessive wave-enhanced bottom shear stresses and sediment suspension in very shallow water. The goals of PET year 5 efforts were, therefore, to investigate and correct these convergence and physics issues, leading to the development of COMAPS version 2.0.

2. **Component models and inter-model communication**

Full details of the COMAPS component models’ physics and parallelization techniques, and the inter-model communication strategies, were given in the previous PET reports mentioned in section 1. These subjects will, therefore, only be briefly described here.

The CH3D-SED model (Spasojevic and Holly, 1994) resulted from the addition of a sediment transport module (SED) to the original CH3D marine circulation code (Chapman et al., 1996). CH3D is based on Reynolds-averaged three-dimensional conservation equations for water mass, momentum, temperature, and salinity. The basic equations are nondimensionalized and adapted for use with a curvilinear horizontal grid and a sigma-layer (terrain-following) vertical grid, (although a z-plane version of CH3D also exists; Johnson et al., 1991). A Mellor-Yamada level 2.5 turbulence closure model is used. Mixed explicit and implicit finite difference discretizations are used and solutions are reached by a mode-splitting technique, where the external mode (barotropic, depth-averaged) motions are calculated at a much smaller time-step than the internal (baroclinic; depth-varying) motions.

The SED module is based on three-dimensional suspended sediment transport equations and active-layer sediment mass conservation equations applied to an arbitrary number of co-existing user-defined sediment size classes. In the active layer, SED accounts for erosion, deposition, and bedload transport. SED is fully integrated with CH3D, using the same horizontal and vertical grids and similar numerical strategies. SED makes use of CH3D velocity fields and, in turn, provides CH3D with time-varying bed elevations and water densities reflecting the presence of suspended sediment.

COMAPS uses a parallel-processing version of CH3D-SED (Bangalore et al., 1999), based on a one-dimensional domain-decomposition approach and the Message Passing Interface (MPI) function library. A pre-processor divides the horizontal grid into a user-specified number of laterally sliced blocks. The number of rows in each block varies in an attempt to equalize the total number of water points in each block. The calculations for each block are performed on an individual processor, with arrays exchanged between neighboring blocks using MPI calls.

The WAM model (WAMDI, 1988; Gunther et al., 1992) is based on the conservation equation for wave action (wave energy divided by frequency) applied to a spherical (longitude-latitude) grid. Wave action is conserved for each component of a user-defined frequency-direction spectrum, with spectral source/sink terms included for wind input, nonlinear wave-wave interaction, whitecapping, and bottom friction. WAM is classified as a third-generation wave model (Komen et al., 1994), based on the level of sophistication used in the calculation of wave-wave interactions. WAM is also a finite difference code, with upwind, explicit terms used for propagation and centered, implicit terms for the sources and sinks.

The COMAPS version of WAM (Welsh et al., 1999) was parallelized using the OpenMP function library. In contrast to MPI, OpenMP offers loop-level parallelism, where high-demand sections of the code are defined as parallel regions, and then calculations for the entire array bounds of the loops are divided among multiple threads. An advantage of OpenMP is that parallelism can be automatically generated using a compiler flag, though not all directives generated in this way will be beneficial. A disadvantage of OpenMP is that it restricts code execution to shared memory platforms. For this reason, COMAPS simulations have been performed using the SGI Origin 3000 platform at ERDC.

The WCBL model (Lee, 1992; Welsh et al., 2000) simulates the interactions of a wave-related bottom boundary layer, a current-related bottom boundary layer, and sediment erosion, suspension, and deposition. The code is based on the work of Grant and Madsen (1979) and Glenn and Grant (1987). WCBL is a point-model in that it does not include advection. It is therefore assumed that the interaction of wave, current, and sediment motions varies slowly horizontally when represented on the spatial and temporal time scales typically used in COMAPS (hundreds of meters to kilometers, and tens of seconds to minutes, respectively). Alternately, this assumption implies that vertical rather than horizontal processes dominate wave-current-sediment interactions. Some details of WCBL physics will be given in section 3.

WCBL is used in COMAPS as a subroutine called by CH3D-SED. This permits the domain-decomposition strategy used in CH3D-SED to be easily passed onto WCBL. The subroutine strategy is an efficient re-use of processors, since WCBL cannot make any calculations until CH3D-SED (and WAM) can offer it inputs, and in the same way, CH3D-SED (and WAM) cannot proceed until WCBL has completed its calculations.

The couplings between CH3D-SED, WAM, and WCBL require the exchange of arrays between the individual models' computational processes. Since WCBL is used as a CH3D-SED subroutine, the communication between those codes is achieved using a straightforward subroutine argument list. In addition, there is no direct communication between WCBL and WAM. Instead, the WAM arrays needed by WCBL, and the WCBL outputs needed by WAM, are routed through communications involving WAM and CH3D-SED and included in the WCBL argument list. WAM and CH3D-SED communicate by means of MPI function calls between the CH3D-SED master process and non-threaded regions of the WAM code. The CH3D-SED master process uses MPI to manage the assembly of grid-wide arrays from slave processes and the distribution of grid-wide arrays among slave processes. A schematic of all communication operations is included in Welsh et al. (2000). The COMAPS user decides on the number of

CH3D-SED/WCBL processes during the domain-decomposition pre-processing stage, then specifies the number of WAM threads at run-time.

3. Overview of coupling physics

The marine bottom boundary layer coupling in COMAPS is computed within the WCBL model. WCBL parameterizes interactions between wave and current boundary layers and related sediment transport. Due to the oscillatory nature of wave motion, wave boundary layers are generally much thinner, but more turbulent, than current boundary layers. In shallow water, where wave motion is significant near the bed, this results in currents perceiving a wave-enhanced bottom roughness, leading to changes in the vertical profiles of currents. If the combined bed shear stress is beyond a critical value, sediment transport will result in the form of ripples or sheet flow. This mobile bed behavior increases bottom roughness, which will influence the wave and current motions. In WCBL, mobile bed geometries and roughness contributions are calculated using the expressions proposed by Grant and Madsen (1982). An additional feedback occurs if sufficient sediment is suspended to cause significant vertical gradients in the density of the water/sediment mix. In such cases, stable stratification has been set up, which will partially damp out vertical turbulent mixing in the wave-current boundary (Glenn and Grant, 1987).

At every horizontal grid point, the WAM inputs to WCBL are near-bed wave orbital velocity, near-bed wave excursion amplitude, and mean wave direction. The CH3D-SED inputs to WCBL are horizontal current components at the lowest half-sigma level, the elevation of the lowest half-sigma level, and sediment class sizes, densities, and bed composition fractions. WCBL then provides WAM with a bottom friction factor and CH3D-SED with a bottom roughness, skin-friction bed shear stresses for each sediment class, total shear stresses inside and above the combined wave-current boundary layer, reference concentrations for each sediment class, and the elevation at which those concentrations apply. Further details on the use of the WCBL outputs are given in section 5.

COMAPS also accounts for wave-current coupling at the air-sea boundary layer. Two effects of waves on currents are represented. Firstly, there is a direct surface momentum transfer due to spatial gradients of the wave field’s radiation stress (Phillips, 1977). Secondly, the presence of waves increases surface roughness, leading to greater wind input to currents (Taylor and Gent, 1978). The latter effect is parameterized in COMAPS through the use of an enhanced CH3D drag coefficient expression which involves the ratio of wave-related surface stress to total surface stress (Janssen, 1991). Breaking waves also have a significant effect on nearshore currents and turbulence, but surf-zone physics are considered out of the scope of COMAPS. The arrays passed from WAM to CH3D for each horizontal grid point are the four components of the radiation stress tensor and the two components of the wave-related stress vector.

Surface current effects on waves are accounted for in COMAPS in both the propagation and source/sink terms of the WAM wave action transport equation. In the propagation calculations, the current vectors directly advect each wave component and spatial variations in the currents cause wave refraction. In the wind input source term, the wind vector relative to each wave component is vectorially shifted to reflect the current-induced propagation. In the bottom friction sink term, a similar current-related shift is applied, since the net velocity of wave components relative to bed roughness elements will be modified by the presence of currents. The form of the WAM whitecapping and wave-wave interaction parameterizations suggests that currents have no effect on these terms, however. Additional minor coupling effects on waves result from the unsteady variation of depths due to storm surges, seiches, and tides. These variations modify depth-related wave refraction and are accounted for in COMAPS. The arrays passed from CH3D to WAM for each grid point are surface current components and water depth.

The frequency of coupling between the component models of COMAPS is set by the user at run time. Welsh et al. (1999) found that the magnitudes of coupling effects can be quite sensitive to the choice of this parameter. For Lake Michigan storm conditions, rapid coupling, on the order of once every three simulation minutes, was found to be necessary. COMAPS also permits the user to choose between noncoupled, one-way coupled (either WAM to CH3D-SED/WCBL only, or CH3D-SED to WAM only – WCBL requires WAM inputs), or two-way coupled simulations.

4. WCBL convergence upgrades

As stated in section 1, the version of WCBL in COMAPS 1.0 commonly had convergence problems in water depths greater than 100m and less than 4m. The causes of nonconvergence were investigated using a stand-alone test version of WCBL, which was run for comprehensive ranges of idealized wave and current inputs. The near-bed wave orbital velocity was varied from 0.00001cm/s to 100000cm/s, (with the wave excursion amplitude, in cm, set equal to the orbital velocity, in cm/s, which is a reasonable zero-order approximation). The reference elevation current was independently varied over the same velocity range. The reference elevation (that is, the lowest half-sigma level) was set to 10cm, 100cm, or 1000cm. The difference between wave and current directions was set to 0 or 45 degrees. In all test runs, three evenly distributed size classes were used, representing typical sand, silt, and clay sediment particles. Simple plots of the regions of nonconvergence were made for each combination of trial reference elevation and directional difference; the axes on these plots covered the ranges of wave and current velocities. Representative runs for each problematic region were then closely traced until three specific causes were identified. The problems and the solutions used are described in subsections 4.1 – 4.3.

Figure 1 shows a representative plot of the nonconvergent regions before and after the convergence investigation. The plot is for a reference elevation of 100cm and a directional difference of 45 degrees. The contours indicate the wave-current bottom shear velocity calculated by WCBL.

4.1 Discontinuous mobile bed roughness

The basic solution strategy in WCBL is to keep estimating the near-bed current until the resulting wave-current boundary layer calculations and current profiles recover the reference elevation velocity provided by CH3D. An important parameter in the current profile is the bottom roughness. In WCBL, the total physical bed roughness is given by

$$k_b = k_{bs} + k_{br} + k_{bt}\,, \qquad (1)$$

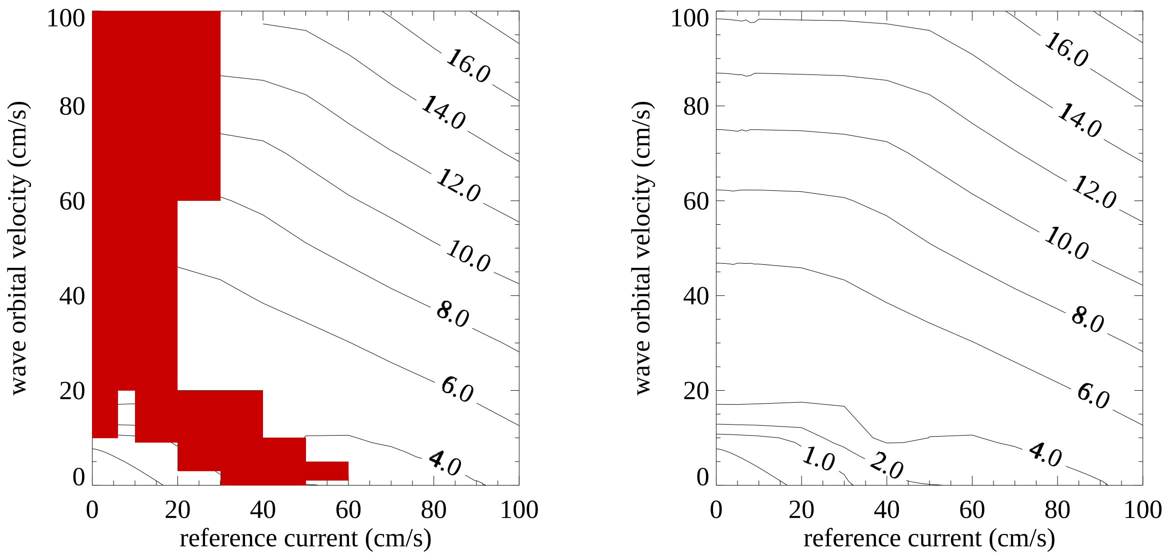

Figure 1: WCBL bottom shear velocity contours (cm/s) before (left) and after (right) convergence investigation. Red zones indicate nonconvergence.

where the three contributions are due to sediment grains, bed ripples, and sheet flow, respectively. The second and third terms are jointly referred to as mobile bed roughness, since they only have a non-zero value when the applied bottom shear stress is at or above the critical value for sediment transport. WCBL calculates ripple and sheet flow dimensions and the associated roughness contributions using the expressions of Grant and Madsen (1982). When the critical bottom shear stress is reached, these roughnesses discontinuously increase from zero to levels that dominate the total bed roughness. In certain common situations this discontinuity prevents WCBL from converging. If the trial value of near-bed current corresponds to a shear stress below the critical value, the resulting reference elevation current is below the input CH3D value, but if the trial near-bed current yields a bottom shear at or above the critical value, the resulting reference current is above the CH3D value. Therefore, convergence is impossible. This problem was removed by introducing two modifications. Firstly, the mobile bed roughness contributions were introduced more gradually. They now linearly increase from zero to their critical shear stress values as the shear moves from 95% to 100% of the critical value, which is in fact more realistic behavior. This change alone was not enough to completely eliminate the convergence problem, however. A rather steep step in the evolution of bottom roughness remained and the standard WCBL Newton-Raphson iteration scheme could still repeatedly overshoot or undershoot the appropriate near-bed current value. The second modification prevented this. A simple bisection iteration scheme was introduced that would take over when the Newton-Raphson scheme failed, working between the nearest trial currents below and above the steep increase in bed roughness.

4.2 Excessive stratification

WCBL includes the suspended sediment stratification theory of Glenn and Grant (1987). One consequence of this theory is the modification of the vertical current profile expression of Grant and Madsen (1979). The profile is modified by the addition of an extra term. In high near-bed wave velocity cases (on the order of 50 cm/s and greater) it was found that this correction term dominates the current profile, imparting a rapid increase in current with elevation above the wave-current boundary layer. Physically, this reflects the reduction of vertical mixing due to the sediment-related stratification. The upward transport of low-momentum fluid by turbulence is reduced, which leads to an increase in the vertical gradient of current. In the conditions described above, the current gradient became so large that no trial value of near-bed current would result in recovery of the CH3D reference elevation current. No matter how small the trial value was, the resulting reference elevation current would exceed the CH3D value. This obviously indicates a breakdown in the realism of the stratification theory. Since the problem is caused by excessive stratification, a number of different modifications were tested, each aimed at reducing the magnitude of the stratification-related term in the current profile. The most successful modification, which was implemented, was the introduction of a simple reduction factor. In the standard formulation, the (trivial) value of this multiplier on the stratification term is 1. If excessive stratification prevents convergence, however, this factor is reduced (in increments of 0.25) until successful convergence is achieved. The large reduction increment is necessary to prevent impracticably large run times for this highly iterative code. The reduction factor is clearly not a theoretically convincing approach. Its use should be taken as acknowledgment that significant work remains in attempts to realistically represent the complex structure and effects of suspended sediment stratification.

4.3 Negligible near-bed wave motion

WCBL convergence was found to breakdown when the near-bed wave-orbital velocity became much smaller than the reference elevation current. Problems began when the ratio fell below 0.0001. This convergence limit is not unexpected, since the theory of Grant and Madsen (1979) was intended to quantify the effect of significant wave motion on the bed roughness perceived by currents. A key dimensionless parameter in their theory is the ratio of physical bed roughness to wave excursion amplitude (k_b / A_b), and many stages of their calculations involve A_b as a denominator. When near-bed wave motion becomes small, therefore, WCBL calculations approach division by zero and iteration schemes oscillate violently between extremely large positive and negative trial values with no hope of convergence. In test runs with negligible wave velocities, this was found to consistently occur in the attempted calculation of the combined wave-current bottom friction factor.

When near-bed wave motions become small, one would hope (regardless of convergence issues) that WCBL predictions would approach those of a traditional current boundary layer approach (e.g. USACE, 2001). Therefore, the negligible wave convergence problem was resolved by the addition of a new current boundary layer (CBL) branch in the WCBL code. For consistency, the assumptions, the order of the calculations, the variable names, and the subroutines called in the CBL code were kept as close as possible to those in WCBL. Iterative solution is not required in CBL since the near-bed current sought in WCBL is no longer needed. CBL proceeds in the following manner:

- The skin friction bed roughness is calculated using the representative (50th percentile by mass) bed grain size. Only skin friction is initially considered since it is the component of bottom stress that is actually felt by sediment grains in the bed, causing their motion and the creation of additional bed roughness in the form of ripples or sheet flow.

- The bottom friction coefficient based on skin friction is calculated.
- The bottom shear stress based on the reference elevation current and skin friction is calculated.
- The critical shear stress for sediment motion is calculated for the representative grain size.
- The mobile bed roughness contribution is calculated using the applied and critical shear stresses. This contribution (if any) is added to the grain roughness (skin friction) to give the total bed roughness. The CBL mobile bed calculations are described below.
- The bottom friction coefficient based on total bed roughness is calculated. This parameter will be returned to CH3D-SED.
- The bottom shear stress based on the reference elevation current and the total bed roughness is calculated. This parameter will be returned to CH3D-SED.
- For each sediment size class, the bottom shear stress based on the reference elevation current and skin friction is calculated. This first requires calculation of the individual skin friction bed roughnesses and friction coefficients, as above. These shear stresses are needed since they are the applied stresses actually encountered by the bed grains of the respective size classes.
- For each size class, the reference suspended sediment concentration (based on the skin friction shear stress) is calculated, as well as the elevation at which this concentration applies. These parameters will be returned to CH3D-SED. More details of the WCBL/CBL reference concentration calculations are given in Section 5.

The mobile bed calculations in CBL are different from those in WCBL. Bottom roughness due to bed ripples is not considered in CBL because ripples are generally caused by oscillatory (wave-related) motion. Current-dominated conditions lead to sheet-flow rather than ripples. The Grant and Madsen (1982) sheet-flow relations used in WCBL are based on wave-dominated conditions, however, so they are not appropriate for use in CBL. Instead, the bedload layer height from Smith and MacLean (1977) is used:

$$h_t = D_{50}\left[\frac{26.3\left(U_*'^2 - U_{*c}^2\right)}{(s-1)g}\right], \tag{2}$$

where D_{50} is the fiftieth percentile grain size by mass, s is the sediment specific gravity, g is gravitational acceleration, U_*' is the bottom shear velocity based on skin friction only and U_{*c} is the critical shear velocity for the initiation of sediment motion. The last two terms are calculated for D_{50}. Equation (2) was derived using data from pure current conditions. By analogy with Grant and Madsen (1982), CBL converts the bedload layer height to an equivalent bottom roughness using

$$k_{bt} = 3.8 h_t . \tag{3}$$

5. Physics upgrades

Adriatic Sea hindcasts performed in PET year 4 (Welsh et al., 2000) suggested that COMAPS version 1.0 predicted excessive wave-enhanced bottom shear stresses and sediment suspension in very shallow water. The causes of this were investigated in PET year 5. As a result, the physics upgrades detailed in the following subsections were implemented in COMAPS version 2.0.

It should be noted that the following text refers to shear stresses while presenting equations formulated in terms of the equivalent shear velocities. This is done for reasons of convention; discussions in the relevant literature are normally framed in terms of shear stress, but the calculations in WCBL are performed using the shear velocity relations shown in the equations. The relation between shear stress and shear velocity is given by

$$\tau = \rho U_*^2 , \qquad (4)$$

where ρ is the water density.

5.1 More physically realistic shear stress parameters for CH3D-SED

The Grant and Madsen (1979) wave-current boundary layer theory calculates a combined shear stress that exists within the relatively thin wave-current boundary layer and a current shear stress that applies in the remainder of the overlying current boundary layer. The calculation of these parameters in WCBL is detailed in Welsh et al. (2000). Due to the highly turbulent nature of the wave-current boundary layer, the combined shear stress is typically much larger than the current shear stress. The combined shear stress is related to the total bed roughness described in section 4.1. The current shear stress reflects the increased, apparent bottom roughness due to the presence of the combined boundary layer. In addition, WCBL follows the Grant and Madsen (1979) theory in the calculation of individual wave-current shear stresses that are applied to each sediment size class in the marine bed. These stresses reflect only the grain roughness (skin friction) of each size class, since bed ripple and sheet-flow roughnesses are not related to individual grains in the bed. The skin friction combined shear stresses are calculated in the same manner as the total roughness combined shear stress, with total roughness simply replaced by individual size class grain roughnesses. These parameters are in fact all calculated within the same iterative solution procedure outlined in section 4.1.

Careful consideration of the physical meanings of each of the WCBL shear stress parameters has led to more appropriate use of the individual parameters in COMAPS 2.0. In COMAPS 1.0, the WCBL total roughness combined shear stress was used in all CH3D-SED calculations that required a bottom or near-bed shear stress. In sediment transport situations, the total roughness shear is much larger than the skin friction shear stresses. This was one cause of the excessive sediment entrainment and suspension mentioned above. The various WCBL shear stresses are now used in the following ways:

- In CH3D, the current shear stress is always used. This is the bottom shear stress perceived by currents above the wave-current boundary layer, which is assumed to lie within the lowest half-sigma layer of CH3D. This assumption only breaks down in very shallow depths, on the order of a few meters, which does not further limit COMAPS since WAM and CH3D-SED are not intended for surf-zone use.

- In SED, the appropriate skin friction bottom shear stress is used for the erosion calculations involving a particular sediment size class. This is the shear stress applied to a grain lying in the bed.
- In SED, suspended grains are subject to the current shear stress since all vertical (sigma layer) nodes will lie above the combined boundary layer, except in very shallow water, as explained above. This use of the current shear stress relates to SED calculations throughout the water column and concerns the balance between turbulent grain suspension and gravitational settling.
- The total roughness wave-current shear stress is no longer used in CH3D-SED.

5.2 Consistent, accurate WCBL and SED critical shear stresses

In COMAPS 1.0, WCBL calculated the critical shear stress for the initial movement of bed sediment grains of a particular size class, *n*, using

$$U_{*cn} = \left(c_1 S_{*n}^{c_2} (s-1) g D_n\right)^{0.5}, \tag{5}$$

where D_n is the grain diameter, and the values of coefficient c_1 and exponent c_2 depend upon the value of the fluid-sediment parameter,

$$S_{*n} = \frac{D_n}{4\nu}\left((s-1) g D_n\right)^{0.5}, \tag{6}$$

where ν is the kinematic viscosity of water. Values of c_1 and c_2 were specified for six different ranges of S_{*n}, with the lowest range covering $0 \le S_{*n} \le 1.5$. USACE (2001) provides additional c_1 and c_2 values for the range $0 \le S_{*n} \le 0.8$, however. This additional range bin is used in COMAPS 2.0, resulting in significant increases in WCBL U_{*cn} for silt and clay size classes, which in turn leads to reduced (more realistic) sediment suspension.

In COMAPS 1.0, SED calculated the critical shear stress for the initial movement of bed sediment using

$$U_{*cn} = \left(0.06 (s-1) g D_n\right)^{0.5}. \tag{7}$$

This is a simpler relation than the WCBL expression, (5), with $\left(c_1 S_{*n}^{c_2}\right)$ effectively set to a constant value for all grain sizes and densities. The use of (7) for silt and clay size classes resulted in severe underestimates of U_{*cn} in SED, leading to overestimated sediment transport. In COMAPS 2.0, the improved WCBL U_{*cn} algorithm (5) described above is also used in SED.

5.3 Consistent WCBL and SED reference concentrations

The reference sediment concentration proposed by Glenn and Grant (1987) and used by WCBL in COMAPS 1.0 is:

$$C_{vrn}(z_0) = C_b \frac{\gamma T_n'}{1+\gamma T_n'}, \tag{8}$$

where $C_{vrn}(z_0)$ is the volumetric fraction reference concentration for size class n at the physical bottom roughness elevation, z_0; C_b is the sediment concentration in the bed, which is set = 0.6; γ is a constant, set = 0.0024; and T_n' is the normalized excess skin friction for size class n, which can be calculated using

$$T_n' = \frac{U_{*n}'^2 - U_{*cn}^2}{U_{*cn}^2}, \tag{9}$$

The roughness height in (8) is calculated using

$$z_0 = \frac{k_b}{30}, \tag{10}$$

where k_b is the total roughness given by (1), with grain roughness, ripple, and sheet-flow terms calculated using $U_*'(D_{50})$.

Equation (8) is based on the expression of Smith and MacLean (1977):

$$C_{vrn}(z_0) = i_n C_b \frac{\gamma T_n}{1+C_b \gamma T_n}, \tag{11}$$

where i_n is the volumetric fraction of all bed sediment which falls within size class n; C_b = 0.65; γ = 0.0024; and T_n is derived using all roughness contributions, not just skin friction.

Comparing (8) and (11) results in the following issues:

- Grant and Madsen (1982) show that for an oscillatory boundary layer, T_n should be replaced by T_n'. The use of the latter in (8) therefore seems reasonable.
- The value of C_b varies. The use of 0.6 in (8) follows Grant and Madsen (1982), which is the source of all sediment concentration and bed roughness theory in Glenn and Grant (1987). It should also be noted that the USACE (2001) recommends C_b = 0.65. There is, however, no

consensus in relevant literature on a consistently appropriate value of C_b, so there appears to be no compelling reason to switch to 0.65.

- i_n is not used in (8) and C_b is not used in the denominator of (8). Both of these omissions have been rectified in COMAPS 2.0. The omission of i_n, in particular, leads to large overestimates of the reference concentrations when multiple sediment size classes are used. Grid-wide arrays of i_n are now supplied to WCBL by CH3D-SED.

WCBL, therefore, now calculates reference concentrations using

$$C_{vrn}(z_0) = i_n C_b \frac{\gamma T_n'}{1 + C_b \gamma T_n'}, \tag{12}$$

with T_n' given by (9), C_b = 0.6, and γ = 0.0024.

The SED model used its standard reference concentration calculation in COMAPS 1.0. This follows the Van Rijn (1984) formulation:

$$C_{vrn}(z_a) = 0.015 \frac{D_n}{z_a} \frac{T_n^{1.5}}{D_{*n}^{0.3}}, \tag{13}$$

where z_a is defined as half the height of a typical bed ripple, which was kept fixed at 10cm; T_n is the normalized excess bottom shear stress; and D_* is the nondimensional grain size, given by

$$D_{*n} = D_n \left(\frac{(s-1)g}{\nu^2} \right)^{1/3}. \tag{14}$$

While SED requires a reference concentration at a rather higher elevation than WCBL (half the ripple height as opposed to z_0), the use of two different formulations, (12) and (13), in COMAPS obviously introduces unnecessary inconsistency. For this reason, (12) is now used as the basis of SED reference concentrations in COMAPS 2.0. The Smith and MacLean (1977) expression was preferred to the van Rijn (1984) expression for two reasons: It is more widely used, and it is easier to derive a half-ripple elevation concentration from (12) for use in SED, rather than a z_0 concentration from (13) for use in WCBL.

In the calculation of suspended sediment stratification terms, WCBL uses the wave-current boundary layer suspended sediment profile of Glenn and Grant (1987). This profile is now used to project the concentration given by (12) for each size class up to the elevation required by SED. This “half-ripple elevation” is found using

$$z_a = h_t + \frac{\eta}{2}, \tag{15}$$

where h_t and η are the respective heights of the sheet-flow and ripples already calculated in WCBL. The sheet-flow layer is included since the ripples will be superimposed upon the top of any such layer.

WCBL, therefore, now provides SED with reference concentrations for each size class, and the elevation, z_a, at which they apply. This brings consistency to the COMAPS reference concentrations. In addition, the calculation of z_a is a major improvement from the previous use of a constant value.

6. Conclusions

The COupled MArine Prediction System (COMAPS) is comprised of parallel-processing versions of the CH3D-SED circulation and sediment transport model, the WAM wind-wave model, and the WCBL bottom boundary layer model. COMAPS also includes inter-model coupling physics at the air-sea and bottom boundary layers. The first fully functioning version of the system, version 1.0, exhibited iteration convergence problems and predicted excessive bed shear stress and sediment suspension in shallow water. A detailed investigation of these issues has now been completed, leading to a number of system upgrades.

The convergence problems occurred in the WCBL coupled bottom boundary layer calculations. A stand-alone test version of WCBL was run using wide ranges of idealized wave, current, and sediment inputs. This allowed identification of the types of input combinations that were problematic. Further investigation of the precise computational mechanism of nonconvergence led to three specific issues:

- The sudden increase in mobile bed roughness at the onset of sediment motion led to a step-discontinuity in total bed roughness. In certain conditions, this meant that no trial value of near-bed current would result in a reference elevation current that matched the CH3D input current, as required for convergence. This was resolved using more gradual introduction of mobile bed roughness, plus the use of a bisection convergence scheme when the standard Newton-Raphson scheme still did not converge.

- In high-wave conditions, the sediment stratification correction term in the theoretical current profile became so large that no matter how small the near-bed current was set, the resulting reference elevation current would always exceed the CH3D input current. This issue was resolved by applying a simple reduction factor, where required, to the correction term. More theoretically convincing approaches to correcting this problem were unsuccessful, suggesting that sediment stratification is not yet fully understood.

- In deep water, wave-related parameters used in the denominators of bottom boundary layer calculations became so small that successive iterative estimates oscillated violently with no hope of convergence. Furthermore, wave-current bottom boundary layer theory is not intended for virtually pure current situations. A pure current boundary layer solution is, therefore, now used in WCBL when near-bed wave motions become negligible. The standard WCBL mobile bed roughness calculations have been replaced in the current boundary layer calculations with parameterizations appropriate to that flow regime.

The excessive shear stresses and sediment concentrations in shallow water were traced to three factors in the SED model; inappropriate use of WCBL shear stress parameters, underpredicted critical shear stresses, and overpredicted near-bed reference concentrations. These issues were resolved as follows:

- For each sediment size class, the wave-current bottom shear stress related to grain roughness only is now used to generate sediment erosion. This is the shear stress actually applied to the sediment grains in the bed and in high stress conditions it is much smaller than the previously used total wave-current shear stress. In addition, suspended sediments grains are now subjected to the current shear stress rather than the wave-current shear stress, since all vertical (sigma layer) nodes lie above the wave-current boundary layer.

- The standard SED model calculation of the critical shear stress for the initiation of sediment motion used the same expression for all sediment sizes and densities. This led to severe underprediction of the critical stresses for silt and clay sizes. SED and WCBL now use the same set of expressions for critical shear stress, which cover all size classes accurately.

- The SED calculation of reference concentration previously used a different relation than that used by WCBL. Furthermore, an unrealistic constant bottom roughness was assumed in the SED calculations. WCBL now supplies SED with more accurate reference concentrations for each size class, as well as spatially and temporally variable bottom roughness conditions.

The implementation of these numerical and physics upgrades has led to the completion of COMAPS version 2.0. The Adriatic Sea hindcasts used in the evaluation of COMAPS 1.0 are now being re-run using version 2.0. The evaluation of COMAPS 2.0 is not yet complete, but it is the authors' expectation that significantly improved predictions will be confirmed, leading to enhanced support for military operations in the marine environment.

Acknowledgment

This work was supported in part by a grant of HPC time at ERDC MSRC from the DoD HPC Modernization Program.

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